

Molten Salt Reactor (MSR)

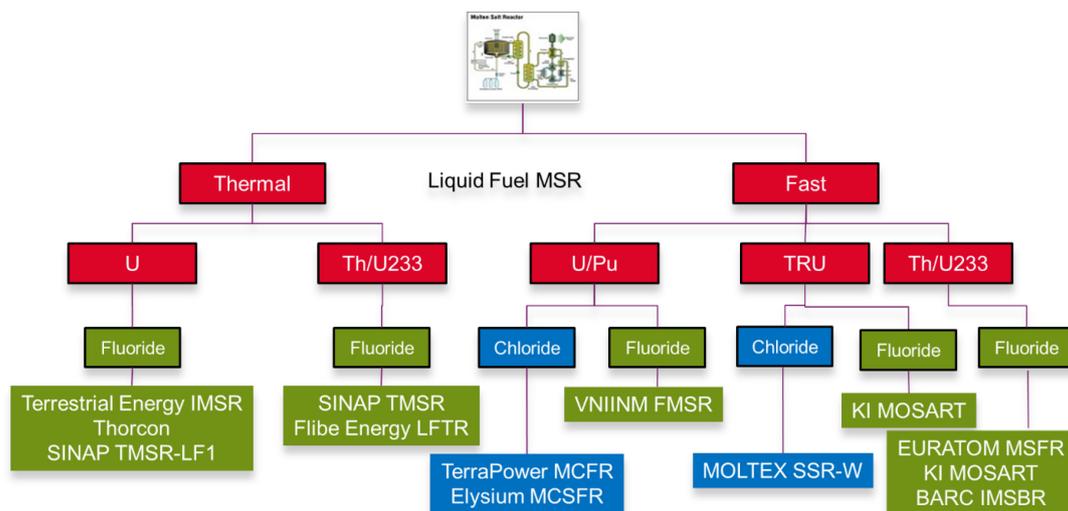
Introduction

Molten Salt Reactor (MSR) concepts have been studied since the early 1950s, but with only one test reactor operated at ORNL in the 1960s. For about 15 years, there is now a renewal in the interest of such a reactor technology, in particular for its acknowledged inherent reactor safety and its flexibility.

MSR uses molten salts as fuel and/or coolant. When a fluoride salt is the coolant only, such concepts are named under FHR (Fluoride salt-cooled high-temperature reactor). Today, in the GIF pSSC MSR, most, not to say all, the studied concepts are actual MSR with a liquid fuel.

MSR is a concept and not a technology. Indeed, the MSR generic name covers thermal and fast reactors, operated with a U/Pu or a Th/233U fuel cycle, or as TRU burners, with a fluoride or a fluoride carrier salt. An illustration of the most studied concept is given in **Figure MSR 1**.

Figure MSR 1. **The most studied MSR concepts, with the key players (RTOs or Vendors)**



Depending on the fuel cycle, MSR can reuse fissile and fertile materials from LWR or they can burn high enriched uranium, plutonium or minor actinides. They have an increased power conversion efficiency (the fission directly occurs in the carrier salt, which transfers its heat to the coolant salt in the heat exchangers). MSR are operated under low pressure, slightly above the atmospheric pressure. They can be deployed as large power reactors or as small modular reactors (SMR). Their deployment is today limited by technological challenges such as high temperature, structure materials, corrosion, etc.

The MSR pSSC includes today seven full members (Australia, Canada, Euratom, France, Russia, Switzerland and United States) and Observers (China, Japan, Korea) and is moving towards a System Arrangement. Mission of MSR pSSC is to support development of future nuclear energy concepts that have the potential to provide significant safety and economic improvements over existing reactor concepts.

R&D objectives

The common objective of MSR projects is to propose a conceptual design with the best system configuration – resulting from physical, chemical and material studies – for the reactor core, the reprocessing unit and wastes conditioning. The mastering of MSR technically challenging technology will require concerted, long-term international R&D efforts, namely:

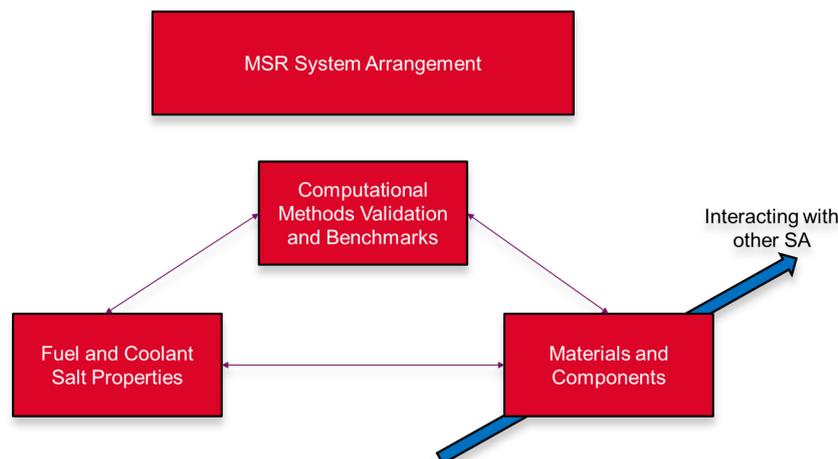
- studying the salt chemical and thermodynamic properties;
- system design: Development of advanced neutronic and thermal-hydraulic coupling models;
- studying materials compatibility with molten salt;
- Salt Redox control technologies to master corrosion of reactor vessel;
- development of efficient techniques of gaseous fission products extraction from the coolant by He bubbling;
- salt reprocessing: reductive extraction tests (actinide-lanthanide separation);
- development of a safety approach dedicated to liquid fueled reactors.

Main activities and outcomes

MSR pSSC activity

In 2019, the key activity was the preparation of the System Arrangements with the definition of three potential Projects Arrangements, which would allow the community to contribute widely. Therefore, these PAs are quite transversal and not concept dependent but can support the development of any concept (see **Figure MSR 2**). They address the salt behavior, the materials properties and the system integration. The SA should enter into force in 2021.

Figure MSR 2. **Foreseen structure of the MSR SA including three PAs**



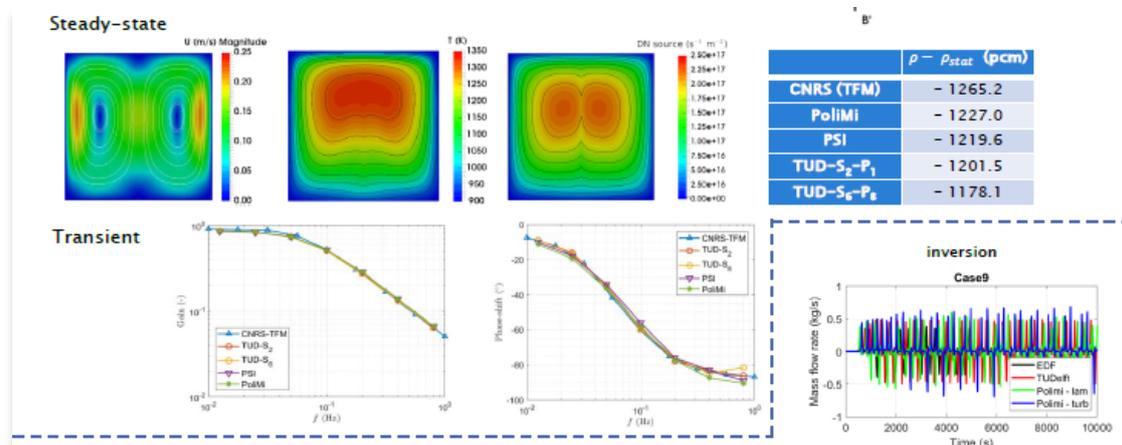
Euratom

European Project SAMOFAR/SAMOSAFER: In the European Union the SAMOFAR project has run successfully under co-ordination of TU Delft for a period of four years from 2015 to 2019 and has been closed by a festive meeting in the theatre of Delft, The Netherlands. This meeting consisted of a students' boot camp at TU Delft organized by the US project NuStem and the EU project SAMOFAR, followed by a two-day meeting presenting the final results of SAMOFAR and with

presentations of representatives from Canada, China, EU, Russia and the United States on the progress made in their respective national research programmes. The boot camp was attended by about 40 students worldwide, while the final meeting was attended by about 100 participants.

At 1 October 2019, the new SAMOSAFER project started aiming at new simulation models and tools, and on new safety barriers for the Molten Salt Reactor. The goal of this new project is to develop and demonstrate new safety barriers for more controlled behavior of Molten Salt Reactors in severe accidents, based on new simulation models and tools validated with experiments. The grand objective is to ensure that the MSR can comply with all expected regulations in 30 years' time. After successful completion of this project, the simulation models and tools can be used by the nuclear industry, and the innovative safety barriers can be implemented in new MSR designs. This will lead to increased safety margins in future Gen-IV Molten Salt Reactors to ensure they will comply with the latest and future safety standards. SAMOSAFER is co-ordinated by TU Delft and will run until 2023.

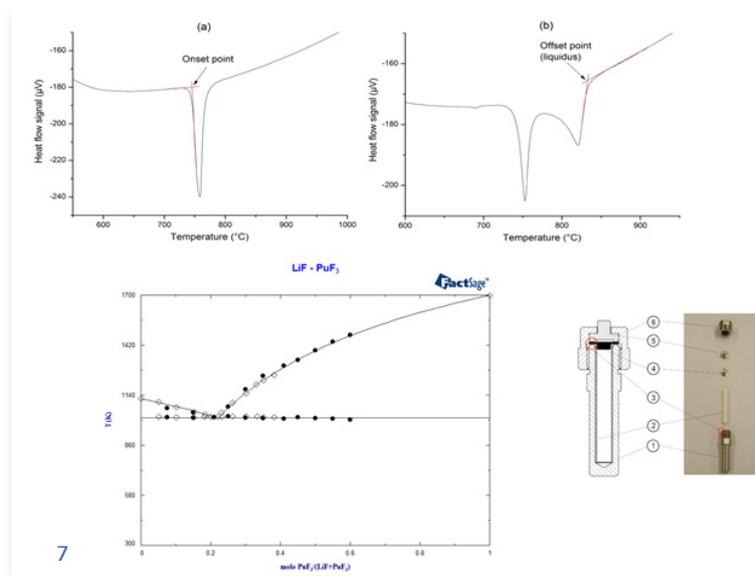
Figure MSR 3. **Multi-physics code for V&V. Benchmark of PoliMi and PSI codes**



A special session on the progress in the Science & Technology of Nuclear Reactors using Molten Salts was organized in collaboration with the European Physical Journal, Nuclear Sciences & Technologies. Guest editors were Jan Leen Kloosterman (TU Delft), Elsa Merle (CNRS) and Jean Ragusa (Texas A&M).

In the Netherlands, the Salient-01 irradiations in the Petten High Flux Reactor were finalized. The samples are currently being investigated in the framework of SAMOSAFER in laboratories at NRG and JRC Karlsruhe. Follow-up irradiations are underway.

JRC Karlsruhe: After successfully establishing the method to synthesise highly pure actinide fluoride salts using HF fluorination line at JRC Karlsruhe, focus was put on development of a chlorination technique to synthesise actinide chloride salts with same high purity. The first tests were done on innovative synthesis of uranium chloride salts from uranium oxide, using a mixture of Cl_2 and CCl_4 gases (carbo-chlorination to convert UO_2 to UCl_4) with successive reduction by H_2 (to convert UCl_4 to UCl_3). By the end of 2019, the first step of the conversion was successful and small quantities of highly pure UCl_4 were obtained.

Figure MSR 4. Phase diagram study of the LiF-PuF₃ system

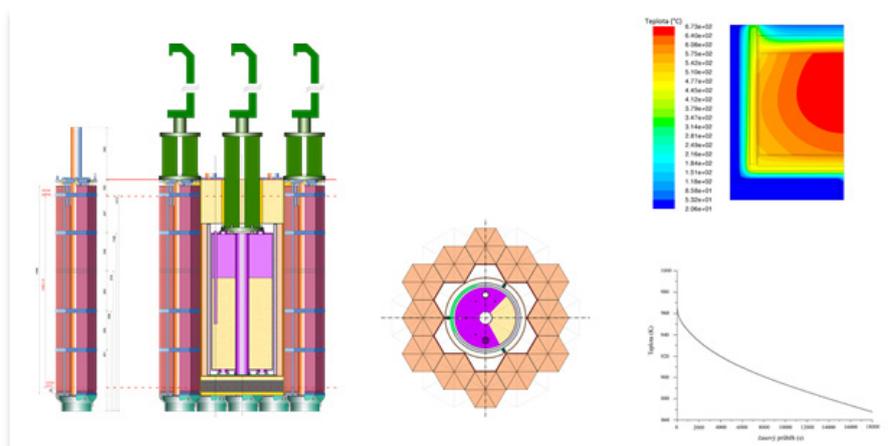
Work on high temperature properties investigation of fluoride salt systems has continued at JRC Karlsruhe with the following highlights:

- First measurements of the melting point of pure PuF₃ have been done. This study still needs optimization, but the experimental set up to determine melting points of actinide fluorides that melt above 1 250°C, which was a limit using standard encapsulation technique, has been established.
- A method to measure thermal conductivity of solid salts, simulating precipitates on the reactor vessel surface, has been improved, achieving successful and reliable measurements using laser flash technique. Thermal conductivity of the series of alkali fluorides has been measured, as well as solidified complex fuel mixtures containing UF₄ and ThF₄ components.
- First trial to test the method to determine solubility of gases in molten salts have been made utilizing high temperature infusion facility with successive quantitative determination of the dissolved gases using effusion cell coupled with quantitative mass spectrometry.

Among experimental studies on basic thermo-chemical properties, JRC is significantly involved in synthesis and fabrication of the fluoride fuel salt for the planned irradiation experiment SALIENT-03 in the HFR (High Flux Reactor) in Petten in a major collaboration with NRG.

Centre Research Řež: In 2019, research and development of MSR technology continued in the Czech Republic also as a part of a national MSR project supported by the Ministry of Industry and Trade and by the Technology Agency of the Czech Republic. The main effort was devoted to the preparation of neutronic measurements with the so-called "Hot Inserted FLIBE Zone" in the experimental reactor LR-0 of the Research Centre Řež. This is a new demanding experimental program whose aim is to determine the reactivity temperature feedback coefficients of the FLIBE melt in the working temperature range of MSR system (500-750°C). By the end of 2019, all the main components of the Hot Inserted FLIBE Zone had been produced. The active experimental program will start in 2020.

Figure MSR 5. Design of the heated zone for FLIBE salt



In addition, the development and testing of impeller pumps for fluoride melt media, in the program of MONICR alloy welding technology optimization and in the long-term MONICR alloy corrosion test program. Research work also continued in the field of the development of electrochemical separation methods from fluoride melt media and a new activity focused on experimental studies and verification of MSR volatile fuel components extraction by Fused Salt Volatilization method was launched in second half of 2019.

France

In addition to the work carried out in SAMOFAR and SAMOSAFER, French partners (CNRS, CEA, FRAMATOME...) worked at building a MSR community around a common roadmap including neutronic and its modelling, fuel salt selection, materials and corrosion to develop a concept of fast reactor using a U/Pu fuel cycle in molten fluoride. In particular, a new project was created at CEA to co-ordinate their activities in the field.

Australia

The widespread deployment of molten-salt-based energy systems, including Molten Salt Reactors requires the development and qualification of materials and components capable of withstanding their challenging operation conditions. Hence, with a view to shortening the time to deployment of MSR low-emission energy generation systems, Australia, is working on the development, manufacturing and testing of suitable structural materials and coatings. In particular, ANSTO continues to collaborate with GIF partners to study and understand the corrosion in FLiNaK of candidate Stainless Steels and Nickel-based alloys, in particular, using ANSTO's large-scale infrastructure, (the OPAL reactor, the Australian Synchrotron, and the Centre for Accelerator Science).

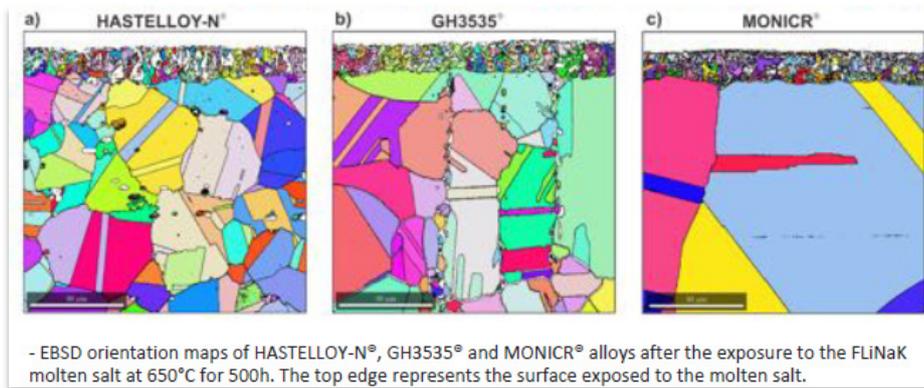
During 2019 Australia continued its initiatives to increase cross-cutting materials related research within GIF. In addition to chairing the GIF Advanced Manufacturing and Materials Engineering Task Force (AMMETF) a joint VHTR/MSR Materials and Components R&D Workshop was held between the MSR pSSC and the VHTR PMB meetings in Avignon in September 2019 designed to identify areas of common research interest.

The workshop was very successful and identified the following potential areas of collaborative R&D:

- advanced manufacturing;
- comparison of ion/neutron radiation damage design methodologies;
- development of creep, and creep-fatigue models;

- high-temperature performance, and radiation damage of graphite, C/C, SiC/SiC;
- small sample testing, and advanced surveillance methodologies;
- welding and joining.

Figure MSR 6. **FLiNAK molten salt corrosion for GH3535, Hastelloy N and MoNiCr alloys**

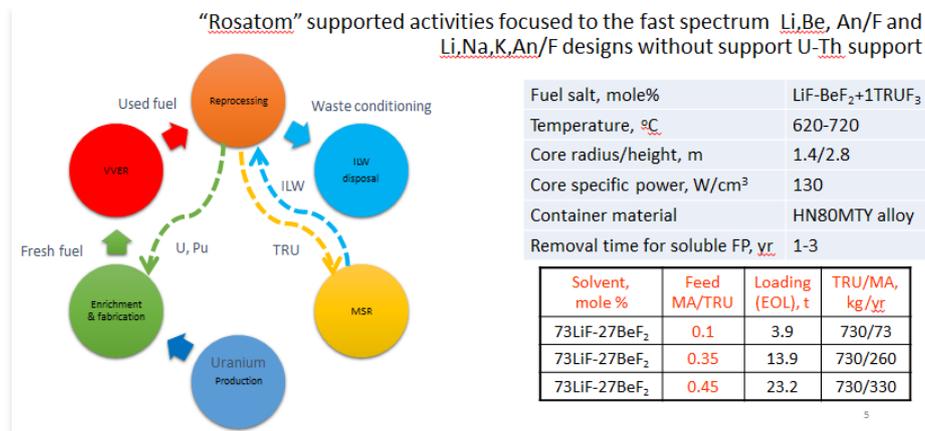


Russia

A significant effort on the molten salt reactor development was performed in the RF in 2019. The State Corporation “Rosatom” has continued to provide support through a number of R&D programs to the single fluid Molten Salt Actinide Recycler & Transmuter (MOSART) system, where minor actinides and plutonium from spent VVER-1000/1200 fuel are dissolved in the liquid fluoride salt. Last developments concerning MOSART design addressed advanced large power Li,Be,An/F and Li,Na,K,An/F units with the main objective to close the nuclear fuel cycle for all actinides, including Np, Pu, Am and Cm. The work was also continued on development of the test 10 MWt Li,Be,An/F MOSART design coupled with fuel salt clean-up unit at the site of the Mining and Chemical Combine (Zheleznogorsk) in order to demonstrate the control of the reactor and fuel salt management with different TRU loadings for start-up, transition to equilibrium, drain-out, shut down, etc. The range of MOSART technology developments currently underway includes:

- high neutron fluence and salt tolerant alloy design property evaluation for fuel Li,Be,An/F and Li,Na,K,An/F salt mixtures;
- both high and low fidelity computational modelling and tool development;
- physical and chemical property measurement for fuel Li,Be,An/F and Li,Na,K,An/F salts;
- molten salt pump & heat exchanger designs and its demonstration;
- instrumentation development;
- highly automated remote operations and maintenance technology development and demonstration;
- fuel salt clean-up demonstration and both solid and gaseous waste stream assessment.

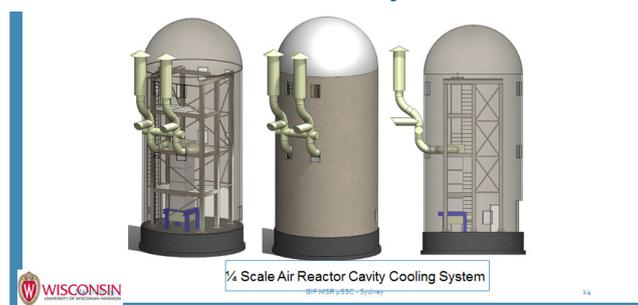
Figure MSR 7. **The MOSART Concept as an integral element helping to solve the problem of long-lived actinides**



United States

A broad range of both molten salt fueled and cooled reactor activities were performed in the United States in 2019. Notably, Kairos Power Inc. continued to file topical reports with the US Nuclear Regulatory Commission (NRC) in preparation for a license application. Also, the Canadian Nuclear Safety Commission and the NRC announced that they have selected Terrestrial Energy’s Integral Molten Salt Reactor for the first joint technical review of an advanced, non-light water reactor under a memorandum of co-operation on advanced reactor and SMR reviews. The US government continues to provide support to the emerging US MSR industry through a number of cost-shared R&D programs. The NRC continues the process of modernizing its licensing requirements to better reflect the safety characteristics of advanced reactors. The US Department of Energy (DOE) continues to support both university and national laboratory activities at limited scale to overcome the remaining technical hurdles to MSR deployment. The US government has also continued work to develop MSR models and associated tools for safeguards analysis. The range of MSR technology developments currently underway includes high neutron fluence and salt tolerant alloy design and property evaluation, both high and low fidelity computational modelling and tool development, graphite testing, fuel salt thermo-physical and thermo-chemical property measurement, fuel salt thermodynamic database development, molten salt pump design and demonstration, instrumentation development, highly automated remote operations and maintenance technology development and demonstration, and both solid and gaseous waste stream assessment. Oak Ridge National Laboratory hosted the annual DOE-Gateway for Innovation in Nuclear supported MSR workshop which featured ~250 participants from industry, the national laboratories, government agencies, international organizations, and academia.

Figure MSR 8. **Air cooled RCGS designed and constructed at University of Wisconsin**



Canada

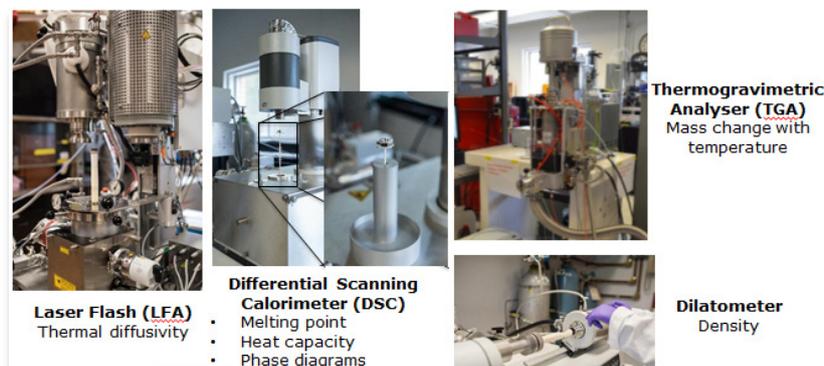
In 2019, Canadian Nuclear Laboratories (CNL) continued to develop expertise and capabilities in support of SMRs and launched a new cost-shared R&D program called the Canadian Nuclear Research Initiative (CNRI). The CNRI program was established by CNL to accelerate the deployment of SMRs in Canada by enabling research and development, and connecting the SMR industry with the facilities and expertise within Canada's national nuclear laboratories. Among the many benefits of the program, participants are able to optimize resources, share technical knowledge, and gain access to CNL's expertise to help advance the commercialization of SMR technologies. In the first intake to this new program three molten salt reactor vendors have submitted proposals with a varied program of work including electrochemical separation methods, tritium management, reactor physics, thermal-hydraulics and safeguards studies.

Under the auspices of the Canadian Federal Nuclear Science and Technology Program, CNL continued to develop molten salt capabilities across a wide range of areas including:

- development of actinide molten salt fuel synthesis;
- fission product retention in molten salt experiments; evaluation of passive cooling during a station blackout with experiments on coupled natural circulation heat transfer between water and molten salt loops and evaluation of molten salt plug melting in accident conditions;
- corrosion loop development for measuring corrosion of structural materials;
- modelling and simulation of Molten Salt Reactor Designs including evaluation of codes for advanced reactor coupled transient simulation toolset against ORNL MSRE: Physics (SERPENT, Rattlesnake); TH (RELAP5-3D, ARIANT); CFD (STAR-CCM+) and atomistic simulations to predict molten salt properties.

Finally significant efforts have continued in further developing nuclear qualified measurement techniques of thermo-physical properties of molten salts.

Figure MSR 9. **Sample encapsulation and measurement technique development at CNL**



Switzerland

The Swiss MSR research is co-ordinated by Paul Scherrer Institute (PSI). In 2019 the PSI continued to develop expertise and capabilities in the three selected areas: fuel cycle, system behavior, and thermo-dynamics of molten salts. The major aim of these simulation activities is the assessment of MSR safety and sustainability. Since PSI is a member of the SAMOFAR and SAMOSAFER projects, part of the PSI activities contribute to the EU progress report.

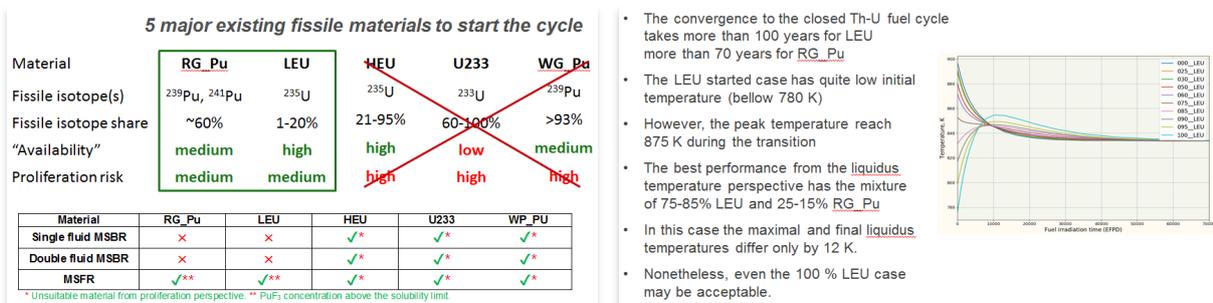
In the area of fuel cycle assessment, several past studies were published in 2019. The result of 16 different reactors comparison in equilibrium fuel cycle, inclusive 4 MSR types, were published. The performance in both U-Pu and Th-U cycles was compared. The breed-and-burn

fuel cycle study from B. Hombourger PhD thesis was published, taking the advantage of special MSR edition of the EPJ Nuclear Sciences & Technologies journal. The breed-and-burn fuel cycle study was further extended by parametric study within MSc thesis and the results will be presented at Physor 2020 conference.

The system behavior study with Open-FOAM based solver continued in 2019 for MSFR core as a H2020 project SAMOFAR contribution. The activities were still ongoing, after the project was finished, and the respective freezing model developed within the project still requires validation. The Open-FOAM based solver was also applied for conceptual designing of own breed-and-burn core thermo-hydraulics layout. The results will be also presented at Physor 2020 conference.

The thermo-dynamics simulation of molten salts was continuing with GEMS TM code, focusing on fluoride-based salts. The liquidus temperature and its evolution during transition from initial to equilibrium fuel cycle was simulated and the results published at ICAPP 2019 Conference. The thermo-dynamics code was also coupled to severe accident code MELCORE to improve the simulation of compounds evaporation from the fuel salt in severe accidents. Towards the end of the year the preparation of the GEMS database for chloride salts started.

Figure MSR 10. **Transition from initial to equilibrium cycle**



China

In 2019, Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP-CAS) is steadily promoting the related work of TMSR.

The design of the 2 MWth molten salt test reactor (TMSR-LF1) was completed and the Preliminary Safety Analysis Report (PSAR) submitted by SINAP to the National Nuclear Safety Administration has passed the examination and approval. In addition, the preparation of key components has been basically completed, and the construction of TMSR-LF1 has begun.

Figure MSR 11. **Progress of the TMSF-LF1**



The construction of the scaled experimental device (TMSR-SF0) has been completed, and the key commissioning activities such as primary and secondary circuit molten salt loading and main pump operation have been successfully completed. The experimental program will be launched in 2020.

Conceptual design of the flowsheets for TMSR fuels is ongoing with validation of some key techniques being finished. Fundamental studies on the chemistry of actinides and fission products in molten salt were started. The PIE experiments of several different kinds of nuclear graphite have been completed, and the evaluation method of irradiation life of nuclear graphite by ion beam irradiation was established. Additionally, the alloys used for high-temperature (750-850°C) MSR are being developed.



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and all Contributors*